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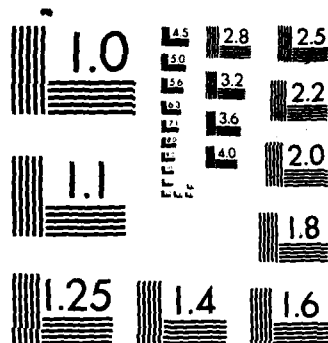
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A BRILLOUIN LIGHT SCATTERING STUDY OF  
MAGNETIC EXCITATIONS

Final Report

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) <b>This report summarizes work accomplished on the above grant, including publi- cations, participating personnel, and degrees awarded. Of particular note are results on exchange in Li-Zn ferrite and surface magnons in thin films. Central to the research was the development of a high contrast, high resolu- tion multipass tandem Fabry-Perot interferometer. The 4-plus-2 system has a contrast in excess of 10<sup>12</sup> and a background dark count below 1/3 count/ second.</b>		

### ABSTRACT

This report summarizes work accomplished on the above grant, including publications, participating personnel, and degrees awarded. Of particular note are results on exchange in Li-Zn ferrite and surface magnons in thin films. Central to the research was the development of a high contrast, high resolution multipass-tandem Fabry-Perot interferometer. The 4-plus-2 system has a contrast in excess of  $10^{12}$  and a background dark count below 1/3 count/second.

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## I. INTRODUCTION

The proposal for this project on Brillouin light scattering in magnetic systems was to set up a multipass-tandem Fabry-Perot interferometer utilizing the best components available and to use the instrument to study a variety of magnetic excitations and materials of fundamental and technological interest. The initial three-year proposal was funded jointly by the ARO and NSF, work commenced in April 1981, and a one-year extension through April 1985 was subsequently funded by NSF. The interferometer became operational in February, 1982. The system has been incorporated into a versatile wavevector and frequency selective spectrometer. The facility has been used to study thermal magnons in  $\text{FeBO}_3$ , exchange in substituted ferrites, parametric spin-waves in epitaxial yttrium iron garnet (YIG) films, surface magnon angle dependence, branch crossover and repulsion for surface and magneto-exchange magnons in thin iron films, and magnetostatic waves in device structures. Results of this work are summarized in Section II of this report. The individual subsections are keyed to the various publications which have resulted from the project. Section III lists all publications on the grant. Section IV lists personnel supported and degrees awarded to those participants. The review section of the original proposal was edited, updated, and published as an issue of Physics Reports [Patton, 1984].

## II. RESULTS

### A. High Contrast Spectrometer

During this initial project, we were able to set up an operational state-of-the-art multipass-tandem Fabry-Perot interferometer and apply the system to a variety of magnetic problems. Design improvements over previous systems at RCA-Zurich (Dr. John Sandercock) and IAF-FhG, Freiburg (Dr. Wolfram Wettling) include a separate, removable stage for the alignment and switching optics, and a high gain, low dark count photon counting system (dark count below one-third count per second). The contrast of the interferometer is in excess of  $10^{12}$ .

Figure II-1 shows a schematic of the Fabry-Perot switching optics. All components on block A are rigidly mounted. Block A is accurately positioned and removable as a unit. This facilitates mirror alignment operations, mirror replacement, etc., without a complete item-by-item alignment requirement. The critical item in the photon counting system is the EMI 9863 A/100 tube, selected for high gain ( $10^6$ ) and low dark count ( $<1$  c.p.s.). The sensitivity is such that phonon peaks in plexiglass of about 200 counts can be detected for a single sweep of the multichannel analyzer. The mechanical design allows for a minimum mirror spacing of about  $50 \mu$ , and a corresponding free spectral range of 3000 GHz, well into the usual Raman spectroscopy regime. The system has been used as the basis for the design of a frequency and wavevector selective magnon spectrometer.



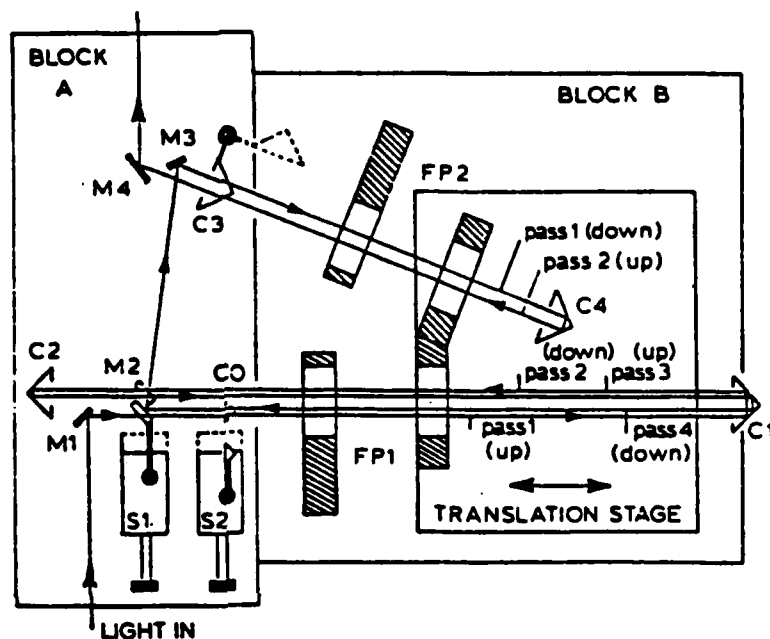


Fig. II-1. Schematic of optical and mechanical components for the tandem multipass Fabry-Perot interferometer. The movable components C0, C3, and M2 allow operation in 0-0, 2-0, 4-0, 0-2, 2-2, 4-2 multipass configurations.

The thermal uniform precession  $k = 0$  mode and the high frequency antiferromagnetic-like magnon branches have been observed in  $\text{FeBO}_3$  for the first time by Brillouin scattering. Brillouin scattering has also been applied successfully to detect the relatively high frequency magnons in orthoferrites. The spectra in Fig. II-2 for  $\text{YFeO}_3$  indicates the high free spectral range which can be achieved with the CSU instrument.

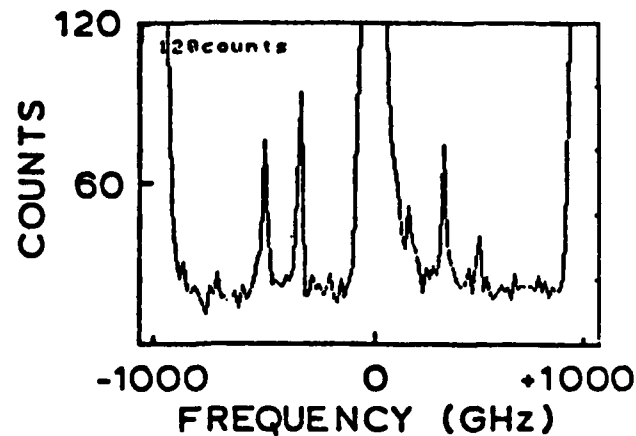


Fig. II-2. Spectrum of  $\text{YFeO}_3$  for a free spectral range of 1000 GHz (microw separation of  $150 \mu!$ ).

"Observation of the High Frequency Spin-wave Branch and the Uniform Precession Mode in  $\text{FeBO}_3$  by Brillouin Scattering," W. Wettling, W. D. Wilber, and C. E. Patton, J. Appl. Phys. 53, 8163 (1982).

### C. Surface Magnons in Thin Films

A considerable effort was devoted to the study of surface magnons in thin films of yttrium iron garnet (YIG) and iron. It was not possible to detect thermal surface magnons in YIG, and the reasons for the lack of any signal whatsoever are not understood. It was possible to detect surface magnons in YIG when excited by external microwave power. These results will be discussed in the section on magnetostatic waves in device structures.

The magnon spectra for iron films turned out to be interesting for both fundamental reasons and device possibilities. It was possible to observe directly the exchange spin-wave branch and magnetostatic surface wave branch crossover. Theoretical work is ongoing to understand the factors which control this branch crossover and repulsion.

"Brillouin Light Scattering Study of Magnon Branch Crossover in Thin Films," P. Kabos, W. D. Wilber, C. E. Patton, and P. Grünberg, Phys. Rev. B29, 6396 (1984). (rapid communications).

The other aspect of the surface magnon spectra which has proved to be quite interesting concerns the angle dependence (angle between the in-plane field and in-plane surface wave propagation wavevector). There is a critical angle at which surface waves cease to be supported for thin film structures. Light scattering has enabled us to observe critical angle effects directly. The observed surface wave dispersion branch folds into the band of bulk magnons at much larger angles (closer to perpendicular) than expected from theory.

"Anomalous Angle Dependence of the Surface Magnon Frequency in Thin Films," P. Kabos, C. E. Patton, and W. D. Wilber, Phys. Rev. Lett. 53, 1962 (1984).

#### D. Parametric Magnons

One of the noteworthy developments during this program was the first use of light scattering to detect paramagnetic half-frequency magnons in YIG films under high power microwave excitation, and to apply wavevector- and frequency-selective methods to map out the wave number and propagation direction characteristics of these magnon instability processes.

"Light Scattering from Parallel Pump Instabilities in Yttrium Iron Garnet," W. Wettling, W. D. Wilber, P. Kabos, and C. E. Patton, Phys. Rev. Lett. 51, 1680 (1983).

"A Brillouin Light Scattering Study of Parametric Magnons in Yttrium Iron Garnet at Microwave Frequencies," W. D. Wilber, Ph.D. Dissertation, Colorado State University, Fort Collins, Colorado, 1986.

Work has also been extended to the problem of parametric magnon processes in hexagonal ferrites. Progress to date has been limited to theoretical extensions to include such systems and microwave measurements of ferromagnetic resonance foldover effects which may involve nonlinear processes. The foldover results led to a new study of foldover in YIG. Light scattering measurements related to these new materials and processes are in progress.

"Spin-wave Instability Theory in Planar Hexagonal Ferrites," M. V. Kogekar, P. Kabos, and C. E. Patton, J. Appl. Phys. 55, 2524 (1984).

"Low Power Nonlinear Effects in the Ferromagnetic Resonance of  $\text{Zn}_2\text{Y}$  and  $\text{MnZnY}$  Hexagonal Ferrites," L. M. Silber, C. E. Patton, and H. F. Naqvi, J. Appl. Phys. 54, 4071 (1983).

"Low Power Nonlinear Effects in the Ferromagnetic Resonance of Yttrium Iron Garnet," K. D. McKinstry, C. E. Patton, and M. Kogekar, J. Appl. Phys. 56, 925 (1985).

#### E. Substituted Spinel Ferrites

One of the challenges in the development of new magnetic materials for high frequency applications concerns the realization of a high magnetization in ferrites. Work in this area was initiated under a previous ARO contract on lithium ferrite. We have developed a new and somewhat more consistent model to calculate the effects of substitutions on the

magnetic properties of spinels and garnets. Light scattering measurements of some such properties, including exchange, have been carried out on zinc substituted Li-ferrite. This work is continuing under a NATO collaborative project with CNR-Rome, with materials emphasis on substituted LPE garnet thin films.

"Localized Canting Models for Substituted Magnetic Oxides," C. E. Patton and Y. H. Liv, J. Phys. C 16, 5995 (1983).

"Brillouin Light Scattering Determination of the Spin-wave Stiffness Parameter in Lithium-Zinc Ferrite," W. D. Wilber, P. Kabos, and C. E. Patton, IEEE Trans. Magnetics 19, 1862 (1983).

#### F. MSW Device Structures

The capability of detecting magnetic excitations directly lends itself to many device applications. In this regard, work has been started on magnetostatic device structures which utilize microstrip microwave transducers to launch magnetostatic waves (MSW). Brillouin light scattering has been used to detect the generated MSW signals, measure their dispersion characteristics, and diagnose device problems.

"Direct Observation of Magnetostatic Wave Excitations in Magnetostatic Wave Device Structures by Brillouin Light Scattering," G. Srinivasan and C. E. Patton, Appl. Phys. Lett. 47, 759 (1985).

"Direct Observation of Surface Wave Excitations in Magnetostatic Wave Devices," G. Srinivasan and C. E. Patton, IEEE Trans. Magnetics 21, 1797 (1985).

### G. Relaxation in Magnetic Systems

Many relaxation processes are operative in magnetic materials. They generally involve coupling between a driven mode (usually the ferromagnetic resonance) and other phonon or magnon modes which are supported by the material or structure. In much the same way that parametric magnons are detected by light scattering, it is possible to detect the magnons or phonons which arise in the course of relaxation processes. It is possible, therefore, to investigate the products of various relaxation processes by direct means, that is, by light scattering on these product excitations. Work toward this goal is proceeding, with emphasis so far on microwave response. The use of Brillouin scattering for magnetic relaxation studies is planned for the near future.

"Microwave Effective Linewidth in Amorphous Co-Ta Films," P. Kabos, T. Kato, T. Mizoguchi, and C. E. Patton, IEEE Tans. Magnetics 20, 1259 (1984).

"Off Resonance Relaxation in Hexagonal Ferrites," J. Magn. Magn. Mat., in press (1986).

### H. Review Articles

The original proposal was edited and published (by invitation) as a review article separate-issue of Physics Reports:

"Magnetic Excitations in Solids," C. E. Patton, Physics Reports 103, 251 (1984).

### I. Follow-Up

During this 4 1/2 year project period, there have been a number of new developments which offer exciting opportunities for light scattering

research on magnetic systems. In the materials area, the discovery of magnetic superlattices and modulated structures as well as the growth of epitaxial magnetic layers on semiconducting material substrates provide new avenues for both basic and applied research. In the area of magnetic phenomena, new types of magnetic order and magnetic phase diagrams for amorphous systems and new types of magnetic excitations in such systems represent effects which can be studied directly by light scattering techniques.

The ongoing program will be enhanced considerably with the recent DOD Instrumentation Grant program award to construct a high-field optical-access cryostat for light scattering research. The recently submitted proposal "A Brillouin Light Scattering Study of Magnetic Excitations and Materials" describes a program, including the topics mentioned above, which utilizes the DOD magnet/cryostat for new work at low temperature and high field.

### III. PUBLICATION SUMMARY

- (1) "Observation of the High Frequency Spin-wave Branch and the Uniform Precession Mode in  $\text{FeBO}_3$  by Brillouin Scattering," W. Wettling, W. D. Wilber, and C. E. Patton, J. Appl. Phys. 53, 8163 (1982).
- (2) "Light Scattering from Parallel Pump Instabilities in Yttrium Iron Garnet," W. Wettling, W. D. Wilber, P. Kabos, and C. E. Patton, Phys. Rev. Lett. 51, 1680 (1983).
- (3) "Brillouin Light Scattering Determination of the Spin-wave Stiffness Parameter in Lithium-Zinc Ferrite," W. D. Wilber, P. Kabos, and C. E. Patton, IEEE Trans. Magnetics 19, 1862 (1983).
- (4) "Low Power Nonlinear Effects in the Ferromagnetic Resonance of  $\text{Zn}_2\text{Y}$  and  $\text{MnZnY}$  Hexagonal Ferrites," L. M. Silber, C. E. Patton, and H. F. Naqvi, J. Appl. Phys. 54, 4071 (1983).
- (5) "Localized Canting Models for Substituted Magnetic Oxides," C. E. Patton and Y. H. Liu, J. Phys. C 16, 5995 (1983).
- (6) "Magnetic Excitations in Solids," C. E. Patton, Physics Reports 103, 251 (1984).
- (7) "Microwave Effective Linewidth in Amorphous Co-Ta Films," P. Kabos, T. Kato, T. Mizoguchi, and C. E. Patton, IEEE Trans. Magnetics 20, 1259 (1984).
- (8) "Anomalous Angle Dependence of the Surface Magnon Frequency in Thin Films," P. Kabos, C. E. Patton, and W. D. Wilber, Phys. Rev. Lett. 53, 1962 (1984).



- (9) "Spin-wave Instability Theory in Planar Hexagonal Ferrites," M. V. Kogekar, P. Kabos, and C. E. Patton, J. appl. Phys. 55, 2524 (1984).
- (10) "A Wavevector Selective Light Scattering Magnon Spectrometer," W. Wettling, W. D. Wilber, W. Jantz, P. Kabos, and C. E. Patton, J. Appl. Phys. 55, 2533 (1984).
- (11) "Brillouin Light Scattering Study of Magnon Branch Crossover in Thin Iron Films," P. Kabos, W. D. Wilber, C. E. Patton, and P. Grünberg, Phys. Rev. B29, 6396 (1984). (rapid communications).
- (12) "Direct Observation of Magnetostatic Wave Excitations in Magnetostatic Wave Device Structures by Brillouin Light Scattering," G. Srinivasan and C. E. Patton, Appl. Phys. Lett. 47, 759 (1985).
- (13) "Low Power Nonlinear Effects in the Ferromagnetic Resonance of Yttrium Iron Garnet," K. D. McKinstry, C. E. Patton, and M. Kogekar, J. Appl. Phys. 56, 925 (1985).
- (14) "Direct Observation of Surface Wave Excitations in Magnetostatic Wave Devices," G. Srinivasan and C. E. Patton, IEEE Trans. Magnetics 21, 1797 (1985).
- (15) "A Brillouin Light Scattering Study of Parametric Magnons in Yttrium Iron Garnet at Microwave Frequencies," W. D. Wilber, Ph.D. Dissertation, Colorado State University, Fort Collins, Colorado, 1986.
- (16) "Off Resonance Relaxation in Hexagonal Ferrites," J. Magn. Magn. Mat., in press (1986).

#### IV. PERSONNEL

The personnel supported on this project in one form or another (Salary, materials, etc.) are listed below.

Principal Investigator:	Carl E. Patton Professor of Physics
Postdoctoral Fellow:	Gopalan Srinivasan Ph.D., IIT-Bombay
Postdoctoral Fellow:	Pavel Kabosh Ph.D., SVST-Bratislava
Visiting Research Fellow:	Wolfram Wettling IAF-FhG-Freiburg
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High School Students:	Saraz F. Naqvi (Rocky Mountain High School) Glen Sunada (Rocky Mountain High School) Robert Clark (CETA Program) Dale Lippert (CETA Program)

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